Static and Dynamic Gait Parameters Before and After Multilevel Soft Tissue Surgery in Ambulating Children With Cerebral Palsy

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Background: Recent studies have questioned the efficacy of releasing hip flexion contractures and the resulting ankle position after tendoachilles lengthening in ambulating children with cerebral palsy (CP).
Methods: Twenty-three ambulatory children with CP underwent 96 soft tissue-lengthening procedures without bony surgery. Preoperative and postoperative clinical and computerized gait data were reviewed.
Results: Static contractures improved reliably, with improvements in all areas measured, including hip flexion contracture (14 degree improvement), hip abduction (19 degree improvement), popliteal angle (26 degree improvement), and ankle dorsiflexion (11 degree improvement). The changes in computerized gait data were less uniform. The knees showed significant benefits, as evidenced by improved maximal knee extension in stance phase (37.3 degree preop and 19.9 degree postop) and at initial contact (51.6 degree preop and 34.8 degree postop). At the hip, a statistically significant improvement was only seen in maximum hip extension in stance phase (minimum hip flexion), and the magnitude of this change was only 4.6 degree (15.3 to 10.7 degree). There were no significant changes at the pelvis. At the ankle, the tendency was toward calcaneal gait after Achilles tendon lengthening, with excessive dorsiflexion seen both in stance (17.3 degree) and at toe off (− 6.9 degree). Tempero-spatial parameters showed improved stride length, but no significant changes in gait velocity or cadence.
Discussion: The persistence of crouch postoperatively, though improved, likely limited the potential changes in hip kinematics. As this study excluded patients undergoing osseous surgery, it is possible that lever arm dysfunction may have contributed to the ongoing crouch. The results of this study suggest that static contractures and knee kinematics improve reliably after soft tissue surgery in children with CP, but that caution must be exercised when considering heel cord lengthening in these children.
Level of Evidence: Therapeutic level II. See Instructions to Authors for a complete description of levels of evidence.

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Spasticity of muscles acting across joints in children with cerebral palsy (CP) renders gait laborious and energy consuming. Multilevel muscle-tendon lengthening (MTL) surgery is widely believed to improve the velocity, appearance, and efficiency of gait in CP patients, with the physical and psychological benefit of a single surgery and recovery period.[1] By enhancing the biomechanics at the hips, knees, and ankles, multilevel MTL can improve both static physical exam parameters and dynamic gait parameters seen on gait analysis. Nonetheless, the effects of multilevel MTL may be difficult to assess as the surgeries are heterogeneous, many incorporate contemporaneous confounding operations on bone, and the disease severity and patient population are extremely varied.

Although single event multilevel surgeries (SEMLS) for CP patients with spastic diplegia has been advocated since the mid 1980s,[2] it was not until the widespread use of gait analysis that outcomes could be objectively assessed and reviewed for the literature. DeLuca et al[3] showed the value of gait analysis in preoperative planning by reporting that more than 50% of surgical recommendations by experienced surgeons were altered after they reviewed kinetic and kinematic data from the gait lab. Similarly, Kay et al[4] reported that preoperative gait analysis resulted in changes in surgical treatment in 89% of patients. McMulkin et al[5] showed a correlation coefficient less than 0.5 between static and dynamic variables, suggesting physical exam findings are inadequate to predict gait kinematics and function. Gait analysis has also been shown to be critical in the postoperative setting, as Kay et al[6] showed that routine postoperative gait analysis results in recommended changes in patient

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care in up to 84% of patients. In terms of evaluating surgical outcomes, Saraph et al[7] used the recommended combination of gait analysis and physical exam evaluation to review 25 patients who underwent multilevel MTL and found significant improvement in sagittal plane kinematics and knee range of motion and function; however, the study included bony realignment procedures so it is difficult to conclude the degree of benefit from the soft tissue procedures in isolation.

In this study, we review preoperative and postoperative gait analyses and the physical exams of 23 patients with CP who underwent MTL of the iliopsoas, adductors, hamstring tendons, and/or achilles tendon. Preoperative and postoperative gait analyses were used to provide an objective assessment of dynamic function, including stride characteristics (gait velocity, cadence, and stride length), duration of stance phase, and kinematic data at the pelvis, hips, knees, and ankles. The physical exam (static) findings were also reviewed, as fixed contractures at the hip and ankle cannot be determined by gait analysis alone.[8]

In a previous study in a similar patient population, Cuomo et al[9] showed that MTL improved validated outcome measures in children with CP. In this study, we hypothesize that multilevel MTL will improve technical outcomes (static exam) and instrumented gait analysis parameters at the pelvis, hip, knee, and ankle in ambulatory CP patients. The specific questions are: (1) Does multilevel MTL improve the static flexion and adduction contractures at the hip, flexion contractures at the knee, and plantar flexion contractures at the ankle? (2) Does multilevel MTL improve temperospatial gait outcomes of cadence, walking speed, stride length, and duration of stance phase in ambulatory CP patients? (3) Are dynamic, kinematic outcomes at the pelvis, hip, knee, and ankle improved with multilevel MTL? (4) Does heel cord lengthening in these patients lead to a calcaneal gait pattern?

METHODS

Patient Selection

After review and approval from the institutional review board, recruitment of patients occurred as part of a prospective multicenter study of multilevel muscle-tendon lengthening in CP patients. Inclusion criteria included a child with a diagnosis of CP aged 4 to 18 years, a history of household or community ambulation, and one or more surgical indications for soft tissue surgery [greater than 30° hip flexion contracture on the Thomas test, less than 30 degree passive hip abduction (with hip in flexion), a greater than 45 degree popliteal angle, and less than 0 degree of passive ankle dorsiflexion with the knee extended and the hindfoot inverted]. All patients underwent surgery at a single institution as indicated by their physical findings, including iliopsoas recession for hip flexion contractures, adductor tenotomies for adduction contractures, hamstring lengthenings for hamstring contractures, and tendoachilles lengthening (TAL) for equinus contractures. Surgical goals were full hip extension, 45 degree of hip abduction, popliteal angle of less than 30 degree, and 5 degrees of ankle dorsiflexion. Soft tissue lengthenings were carried out in isolation; that is, no patients underwent any corrective bony procedures. Final decisions regarding surgical management were made by the operating surgeon in the operating room and were based on preoperative static exam findings and results from the exam under anesthesia (EUA). The EUA was used to confirm a true, fixed contracture and therefore no release or lengthening was carried out on a joint that achieved the goal range of motion during the EUA. The 2 patients who were enrolled but ended up undergoing only single level surgery owing to the results of the EUA were excluded from this analysis.

Surgical procedures were standardized and carried out by a single surgeon. The iliopsoas was lengthened over the pelvic brim as described by Sutherland.[10] Adductors were released through an open approach. The hamstrings were lengthened both medially and laterally with an open procedure. The TAL were carried out with a Z-lengthening through an open approach.

Each patient received standard postsurgical care including casting or bracing to maintain correction of their deformities in the acute postsurgical setting. All patients undergoing Achilles tendon lengthening were placed into below-knee plaster casts (short leg casts) for 3 weeks with the ankle at zero to 5 degrees of dorsiflexion. The casts were then replaced with ankle foot orthoses molded to prevent plantarflexion, which were worn for at least 6 to 8 hours during the day. All patients undergoing hamstrings lengthening were prescribed night splints, such as knee immobilizers, for a period of 6 weeks to assure healing of any hamstrings procedure in the lengthened position. Patients who had adductor releases were immobilized in an A-frame for 4 weeks postoperatively. Patients undergoing iliopsoas recession were not immobilized. There was no routine use of antispasmodic medications.

The physical therapy program was also standardized. It consisted of stretching, isotonic strength training using free weights, and gait training for 3 sessions per week for the first 6 months. This decreased to 2 sessions per week after the first 6 months. The aims of physical therapy were to achieve full hip extension, at least 150 degree of knee extension, 90 degree of total abduction, at least 5 degrees of ankle dorsiflexion, regain the preoperative level of muscle control and strength, and attain their preoperative ambulatory status. Two sets of logbooks were kept documenting the progress with therapy—1 by the therapist and 1 by the family.

The patients were all assessed by clinical examination and gait analysis at presurgical baseline and at their 12 months postsurgery clinic visit. The gait analyses were done using an 8 camera VICON (Los Angeles, CA) system, which uses 15 to 19 passive retroreflective markers attached to bony landmarks of the pelvis and lower extremities. With the markers in place, each participant walked at a self-selective pace without a brace

TABLE 1. Patient Demographics

Pt #	Age at Surgery (y)	No. Procedures	Total Follow-up (mo)
1	6	4	21
2	7	6	33
3	7	6	15
4	7	4	18
5	7	6	13
6	7	6	12
7	8	8	30
8	8	6	30
9	8	2	27
10	8	2	24
11	8	6	12
12	8	4	12
13	9	4	30
14	10	2	17
15	10	2	23
16	10	4	23
17	10	2	23
18	11	4	25
19	11	2	22
20	11	4	13
21	13	8	15
22	13	2	26
23	14	2	13
Average	9.2	4.2	20.7

along a 15-m walkway. Three dimensional joint motion (kinematic) data were collected for every 2% of the gait cycle for multiple strides. Temperospatial data of cadence, walking speed, and stride length were also measured. Physical exams were carried out by the operating surgeon preoperatively and postoperatively, and static exam parameters measured with a long-armed goniometer included hip flexion contracture, hip abduction angle, popliteal angle, and range of ankle dorsiflexion.

Statistical Methods

The data were assumed to be nonparametric in distribution and thus, Wilcoxon signed rank tests were used to detect significant differences between preoperative and postoperative data sets.

RESULTS

Twenty-three ambulatory patients with CP were identified, enrolled, and evaluated in the study. Patient ages ranged from 6 to 14 (mean 9.2 y). The mean number of surgical procedures carried out was 4.2 per patient (range: 2 to 8). The surgical procedures carried out were 26 iliopsoas releases, 14 adductor tenotomies, 40 hamstring lengthenings, and 16 TAL. The total follow-up averaged 20.7 months (range 12 to 33), but technical outcomes and postoperative gait analysis included in the study were done at the 12-month postoperative visit (Table 1).

The technical outcomes show that the surgical releases improve the static exam of the corresponding contracture (Table 2).

The temperospatial data shows a statistically significant improvement in stride length (66 to 75 cm), but only trends toward improvement in walking speed (0.63 to 0.69 m/sec) and cadence (110.39 to 94.41). The duration of stance phase remained relatively unchanged after MTL (Table 3).

There are no significant changes in pelvic tilt and rotation throughout the gait cycle between the preoperative and postoperative gait studies (Table 4). Hip kinematics show a statistically significant improvement of the maximum hip extension in stance phase (minimum hip flexion), but no other statistically significant improvements (Table 5). At the knee, statistically significant sagittal kinematic improvements were seen throughout the gait cycle, though the timing of peak knee flexion did not change significantly (Table 6). All ankle parameters showed a statistically significant increase in dorsiflexion on postoperative gait analysis after TAL (Table 7). However, both peak dorsiflexion in stance phase and sagittal ankle angle at toe-off were more than 1 standard deviation more dorsiflexed than normal, indicating a calcaneal gait pattern.

DISCUSSION

Current thinking regarding ambulatory children with cerebral palsy is grounded in the concept that the deformities are multilevel in nature,[11,12] and that the optimal outcome is achieved when all contractures of the hip, knee, and ankle have been corrected.[13] SEMLS are thought to be the most efficient, least disruptive method to improve multiple deformities as it limits risks of multiple operations and the psychological and physical burden of multiple recovery periods. These surgeries are, however, notably difficult to assess as there is great variability in the surgery (some including bony realignment) and significant heterogeneity in the patient population. In addition, the postoperative changes at 1-level impact the alignment and function at other levels. Critically, it is not sufficient to ask whether the multilevel procedure benefited the patient as a single entity, but

TABLE 2. Technical Outcomes

	Preoperative Mean	Postoperative Mean	*P*
Hip flexion contracture (IP) N = 26	23.80 (6.1)	9.81 (7.7)	< 0.0001
Hip abduction (ADD) N = 14	29.28 (7.4)	48.57 (13.1)	0.001
Popliteal angle (HAM) N = 40	65.10 (15.4)	39.60 (19.6)	< 0.0001
Ankle dorsiflexion (TAL) N = 16	− 4.38 (5.6)	6.88 (6.0)	0.001

Values in parentheses represent standard deviations.
ADD indicates adductor lengthening; HAM, hamstring lengthening; IP, iliopsoas lengthening; TAL, tendoachilles lengthening.

TABLE 3. Temperospatial Outcomes

	Preoperative Mean	Postoperative Mean	*P*
Cadence (steps/min)	110.39 (31.6)	94.41 (32.3)	0.081
Walking speed (m/s)	0.63 (0.3)	0.69 (0.4)	0.287
Stride length (m)	0.66 (0.2)	0.75 (0.2)	0.010
Duration of stance phase (msec)	69.28 (7.3)	69.30 (8.1)	0.984

Values in parentheses represent standard deviations.
m indicates meters; m/s, meters per second; min, minutes; msec, millisecond.

whether each single muscle-tendon lengthening improved function at the joint that it was designed to affect.

Our results suggest that isolated soft tissue surgery in ambulatory children with CP improves static measurements, but has variable effects on gait parameters in these children. The postoperative evaluations show improved static sagittal plane deformity on physical exam and improved walking speed and stride length on gait analysis. However, the procedures did not uniformly improve dynamic alignment across all joints. Anterior pelvic tilt, maximum hip flexion and hip flexion at initial contact did not improve significantly, whereas nearly all knee parameters improved significantly. After TAL, there was noted to be excessive maximal ankle dorsiflexion in stance phase and increased ankle dorsiflexion at toe off, both of which indicate a calcaneal gait pattern. The absence of significant residual hip flexion contractures, along with the presence of excessive ankle dorsiflexion and knee flexion postoperatively suggest that the persistent hip and pelvic kinematic abnormalities are likely to be at least partially owing to abnormalities at other levels in the lower extremities. Such causes would include the sagittal kinematic abnormalities cited, in addition to potential lever arm dysfunction owing to torsional malalignment and/or foot deformities in this patient group who did not undergo bony surgery.[14] In addition, the use of ankle foot orthotics to correct the excessive ankle dorsiflexion in patients with excessive dorsiflexion would be expected to decrease the crouch gait and improve sagittal kinematics at the hip and knee. In comparison to data previously published in the literature, our patients benefited from similarly significant improvements in stride length and trends toward improvement in speed and cadence of gait (Table 8). Our cohort did not achieve the statistically significant improvement in walking speed that the cohorts in McMulkin et al and Saraph et al did; however, in a cohort with a more similar preop speed, Yngve et al[16] also showed a trend toward increased speed rather than a statistically significant increase. This study also confirms the excess dorsiflexion after TAL that was showed by both Saraph et al[17] and Adolfsen et al.[15,18]

There are several limitations to this study that deserve mention. First, there is some question as to the persistence of gait improvement after multilevel MTL. Saraph et al[17] did serial gait analysis studies 1, 2, and 3 years after single session multilevel surgery and found a persistent decrease in gait function over time after surgery. Other authors have not found such deterioration. In fact, Harvey et al[18] reported that functional mobility, which initially decreased by both 3 and 6 months after SEMLS, returned to baseline by 1-year postoperatively, and then improved in the second postoperative year. Adolfsen et al[15] reported that the improvements in kinematic and kinetic gait parameters seen 1 year after multilevel soft tissue surgery (rectus transfers combined with hamstring and gastrocsoleus lengthening) in 31 ambulatory children with cerebral palsy were maintained 4-year postoperatively. Ounpuu et al[19] have also shown that improvements in gait, which are seen 1 year after femoral rotational osteotomies are maintained at 5 years. On the basis of these differing data, it is possible our data collected at a 1-year postoperative evaluation cannot be extrapolated to long-term follow-up. However, there is an existing body of literature suggesting that the natural history of ambulation in CP patients who *do not* undergo surgery may include worsening contractures and gait parameters,[20] suggesting that perhaps we have underestimated the effects of surgery by comparing the outcomes to a single, preoperative level. Regardless, this question requires further long-term follow-up data.

Another limitation is whether the heterogeneous set of muscle-tendon-lengthening procedures carried out in this study inherently confound the results. Adolfsen et al

TABLE 4. Gait Analysis: Pelvis

	Preoperative Mean	Postoperative Mean	*P*
Pelvic tilt @ contact (degrees)	15.31 (7.3)	18.17 (8.2)	0.092
Pelvic tilt @ midstance (degrees)	19.10 (4.2)	22.00 (4.6)	0.230
Mean anterior pelvic tilt (degrees)	18.45 (10.2)	20.87 (9.0)	0.281
Mean pelvic rotation (degrees)	0.93 (6.6)	0.35 (7.2)	0.685

Values in parentheses represent standard deviations.

TABLE 5. Gait Analysis: Hip

	Preoperative Mean	Postoperative Mean	*P*
Hip flexion @ contact	51.73 (11.5)	49.00 (10.6)	0.204
Minimum hip flexion	15.36 (12.9)	10.67 (11.1)	0.019
Maximum hip flexion	52.03 (11.8)	49.98 (11.2)	0.306
Hip range of motion	37.59 (12.4)	40.29 (11.3)	0.297
Midstance hip rotation	1.09 (10.3)	− 0.76 (9.7)	0.347
Peak abduction in swing	2.15 (7.2)	1.28 (5.3)	0.580

All values are in degrees. Values in parentheses represent standard deviations.

TABLE 6. Gait Analysis: Knee

	Preoperative Mean	Postoperative Mean	P
Flexion at contact	51.60 (14.2)	34.82 (14.7)	< 0.001
Minimum flexion in stance	37.32 (19.1)	19.95 (17.6)	< 0.001
Maximum flexion in swing	67.16 (15.1)	51.75 (14.1)	< 0.001
Timing of peak flexion (% gait cycle)	83.90 (7.1)	84.00 (5.1)	0.942

All values are in degrees. Values in parentheses represent standard deviations.

suggest that outcome studies "need to focus on groups of children with the same combinations of procedures and to evaluate the overall outcomes at all joints."[18] Although we had this limitation in mind as we excluded any patient who required bony realignment procedures, it is true that we included patients who underwent different combinations of soft tissue procedures. Although this does add to the complexity of interpreting that data, we must accept that there is enormous heterogeneity in multilevel MTL surgery and very few centers are able to produce large quantities of data for identical surgeries, given the varying individual needs of each patient. Additionally, the patient population is so heterogeneous that even "identical" procedures are far from identical when consideration is made to the specific patient. To account for the heterogeneity of the patient population, we elected to undertake this study with a discrete group of surgical goals: full hip extension, 45 degrees of hip abduction, less than 30 degrees of popliteal angle, and 5 degrees of ankle dorsiflexion. Although we do not espouse these surgical goals as the "correct" approach to MTL, they certainly provide a framework within which a reader can interpret the results of this study. Further studies with a more standardized surgical approach are undoubtedly needed.

Finally, we point out that we did not stratify patients based on Gross Motor Function Classification System (GMFCS) in this cohort. Although we included patients who were community or household ambulators only, the data on specific GMFCS levels was not clearly demarcated in a number of the preoperative assessments and therefore an adequate analysis based on this variable could not be done. A study stratifying results of multilevel MTL by GMFCS level would be valuable future research.

In this study, musculotendinous lengthening in children with CP reliably improved static contractures, but did not always result in improved kinematics during gait. The knees of our patients showed significant benefits, as evidenced by improved maximal knee extension in stance phase (37.3 degree preop and 19.9 degree postop) and at initial contact (51.6 degree preop and 34.8 degree postop), and improved stride length. Not surprisingly, as rectus transfers were not done, the knee range of motion arc changed little (29.8 degree preop and 31.8 degree postop). At the hip, a statistically significant improvement was only seen in maximum hip extension in stance phase (minimum hip flexion), and the magnitude of this change was small (from 15.4° to 10.7°). There were no significant changes at the pelvis. At the ankle, the tendency was toward calcaneal gait after Achilles tendon lengthening, with excessive dorsiflexion seen both in stance (17.3°) and at toe off (−6.9 degree). Tempero-spatial parameters showed improved stride length, but no significant changes in gait velocity or cadence.

The persistence of crouch postoperatively, though improved from preoperative crouch, likely contributed to the lack of improved hip kinematics in our patients. The tendency toward calcaneal gait and/or deformity after Achilles tendon lengthening is common in children with CP and has been reported in up to 36% of patients in other studies.[21,22] Although calcaneal gait has been reported in children with cerebral palsy who have not had previous heelcord lengthening,[23] and a significant pes valgus deformity may make ankle dorsiflexion seen falsely increased in stance phase, the calcaneal gait described in this series seems owing to truly excessive ankle dorsiflexion rather than breakdown of the midfoot. Although the average postoperative dorsiflexion in the 17 ankles that underwent TALs was only 6.9 degree, 11 of the patients had greater than 10 degree of dorsiflexion and 4 patients had greater than 15 degree of dorsiflexion. The use of solid ankle foot orthoses in our patients with calcaneal gait may have enhanced their hip kinematics (and may have also further enhanced their knee kinematics). Correction of lever arm dysfunction, if present, could potentially decrease crouch as well.

TABLE 7. Gait Analysis: Ankle

	Preoperative Mean	Postoperative Mean	P
Angle at initial contact	−3.23 (10.9)	1.85 (9.4)	0.077
Dorsiflexion at midstance	3.36 (15.4)	9.15 (8.3)	0.090
Peak dorsiflexion in stance	10.71 (15.9)	17.25 (8.2)	0.050
Angle at toe off	−18.05 (21.1)	−6.87 (11.8)	< 0.001
Mean foot progression angle	6.60 (14.2)	−1.70 (13.7)	< 0.001

All values are in degrees. Values in parentheses represent standard deviations.

TABLE 8. Temperospatial Data Comparison to the Literature

	Current Study	Adolfsen et al[15]	McMulkin et al[5]	Yngve et al[16]	Saraph et al[7]
Walking speed (m/s)					
Preoperative	0.63	1.05	0.80	0.57	1.06
Postoperative	0.69	1.09	0.93	0.60	1.19
P	0.287	0.119	0.05	0.20	0.0005
Stride length (m)					
Preoperative	0.66	0.92	0.83	0.63	0.95
Postoperative	0.75	1.02	0.95	0.72	1.13
P	0.010	0.0001	0.018	0.04	0.0001
Cadence (steps/min)					
Preoperative	110.39	136	115.1	107	133.8
Postoperative	94.41	128	117.9	99	126.1
P	0.081	0.0001	0.63	0.02	0.0003

m indicates meters; m/s, meters per second; steps/min, steps per minute.

It is important to remember, however, that these patients were a select population of household or community ambulators preoperatively, and the findings of this study may not be applicable to all children with CP. Orthopaedic surgical treatment for individual patients remains highly individualized to achieve the best possible functional results.

REFERENCES

1. Gannotti M, Gorton GE III, Nahorniak MT, et al. Post operative gait velocity and mean knee flexion in stance of ambulatory children with spastic diplegia four years or more after multilevel surgery. *J Ped Orthop*. 2007;27:451–456.
2. Browne AO, McManus F. One-session surgery for bilateral correction lower limb deformities in spastic diplegia. *J Ped Orthop*. 1997;7:259–261.
3. DeLuca PA, Davis RB III, Ounpuu S, et al. Alterations in surgical decision making in patients with cerebral palsy based on three-dimensional gait analysis. *J Ped Orthop*. 2007;17:608–614.
4. Kay RM, Dennis S, Rethlefsen S, et al. The effect of preoperative gait analysis on orthopaedic decision making. *Clin Orthop Relat Res*. 2000;372:217–222.
5. McMulkin ML, Gulliford JJ, Williamson RV, et al. Correlation of static to dynamic measures of lower extremity range of motion in cerebral palsy and control populations. *J Ped Orthop*. 2000;20: 366–369.
6. Kay RM, Dennis S, Rethlefsen S, et al. Impact of postoperative gait analysis on orthopaedic care. *Clin Orthop Relat Res*. 2000;374: 259–264.
7. Saraph V, Zwick EB, Zwick G, et al. Multilevel surgery in spastic diplegia: evaluation by physical examination and gait analysis in 25 children. *J Ped Orthop*. 2002;22:150–157.
8. DeLuca PA. The use of gait analysis and dynamic electromyogram in the assessment of the child with cerebral palsy. *Sem Orthop*. 1989;4:256–276.
9. Cuomo AV, Gamradt SC, Kim CO, et al. Health-related quality of life outcomes improve after multilevel surgery in ambulatory children with cerebral palsy. *J Pediatr Orthop*. 2007;27:653–657.
10. Sutherland D, Zilberfarb J, Kaufman K, et al. Psoas release at the pelvic brim in ambulatory patients with cerebral palsy: operative technique and functional outcome. *J Pediatr Orthop*. 1997;5: 563–570.
11. Baker LD. A rational approach to the surgical needs of the cerebral palsy patient. *J Bone Joint Surg Am*. 1956;38:313–323.
12. Eggers GW, Evans EB. Surgery in cerebral palsy. *J Bone Joint Surg Am*. 1963;45:1275–1305.
13. Reimers J. Static and dynamic problems in spastic cerebral palsy. *J Bone Joint Surg Br*. 1973;55:822–827.
14. Gage JR, Novacheck TF. An update on the treatment of gait problems in cerebral palsy. *J Pediatr Orthop B*. 2001;10:265–274.
15. Adolfsen S, Ounpuu S, Bell K, et al. Kinematic and kinetic outcomes after identical multilevel soft tissue surgery in children with cerebral palsy. *J Pediatr Orthop*. 2007;27:658–667.
16. Yngve DA, Scarborough N, Goode B. Rectus and hamstring surgery in cerebral palsy: a gait analysis study of results by functional ambulation level. *J Pediatr Orthop*. 2002;22:672–676.
17. Saraph V, Zwick EB, Auner C, et al. Gait improvement surgery in diplegic children: how long do the improvements last? *J Pediatr Orthop*. 2005;25:263–267.
18. Harvey A, Graham HK, Morris ME, et al. The Functional Mobility Scale: ability to detect change following single event multilevel surgery. *Dev Med Child Neurol*. 2007;49:603–607.
19. Ounpuu S, DeLuca P, Davis R, et al. Long-term effects of femoral derotation osteotomies: an evaluation using three-dimensional gait analysis. *J Pediatr Orthop*. 2002;22:139–145.
20. Gough M, Eve LC, Robinson RO, et al. Short-term outcome of multilevel surgical intervention in spastic diplegic cerebral palsy compared with the natural history. *Dev Med Child Neurol*. 2004;46: 91–97.
21. Segal LS, Thomas SE, Mazur JM, et al. Calcaneal gait in spastic diplegia after heel cord lengthening: a study with gait analysis. *J Pediatr Orthop*. 1989;9:697–701.
22. Borton DC, Walker K, Pirpiris M, et al. Isolated calf lengthening in cerebral palsy. Outcome analysis of risk factors. *J Bone Joint Surg Br*. 2001;83:364–370.
23. Wren T, Rethlefsen S, Kay R. Prevalence of specific gait abnormalities in children with cerebral palsy: influence of cerebral palsy subtype, age, and previous surgery. *J Pediatr Orthop*. 2005;25:79–83.

